



Jet Propulsion Laboratory  
California Institute of Technology

# AFTA Coronagraph Science

Wesley Traub

Jet Propulsion Laboratory, California Institute of Technology

Bruce Macintosh

Lawrence Livermore National Laboratory

and members of the the Exoplanet Exploration Program at JPL

WFIRST-AFTA SDT meeting

9 January 2014

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# Outline



ExoPlanet Exploration Program

- Coronagraph down-select process (Dec. 2013)
- Updated capabilities of the prime & backup coronagraphs
  - RV planets
  - New planet discoveries
  - Disk detections
- Work needed
  - Extend coronagraph models to all wavelength bands
  - Refine telescope jitter models
  - Carry out telescope thermal models
  - Design LOWFSC system
  - Evaluate post-processing with new jitter/thermal/LOWFSC
  - Estimate new planet discovery rates
  - Lab validations



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# Purpose and Approach



Exoplanet Exploration Program

- **Objective:** Recommend a primary and backup coronagraph architecture to focus design and technology development to **maximize readiness for new mission start in FY17**
- Recommendation by ExEPO and ASO based on inputs from
  - **AFTA SDT:** Sets the science requirements
  - **ACWG:** Delivers technical FOMs and technology plans
    - > *Aim for the positive: a consensus product*
    - > SDT delivers science FOMs
  - **TAC:** Analysis of technical FOM, TRL readiness plans, and risks
- **ExEPO and ASO** recommendation to **APD Director** based on:
  - Technical and Programmatic criteria
  - Musts (Requirements), Wants (Goals), and Risks
  - Opportunities
- **APD Director** will make the decision

**ACWG = AFTA Coronagraph Working Group:** representatives of ExEPO, ASO, SDT, Community

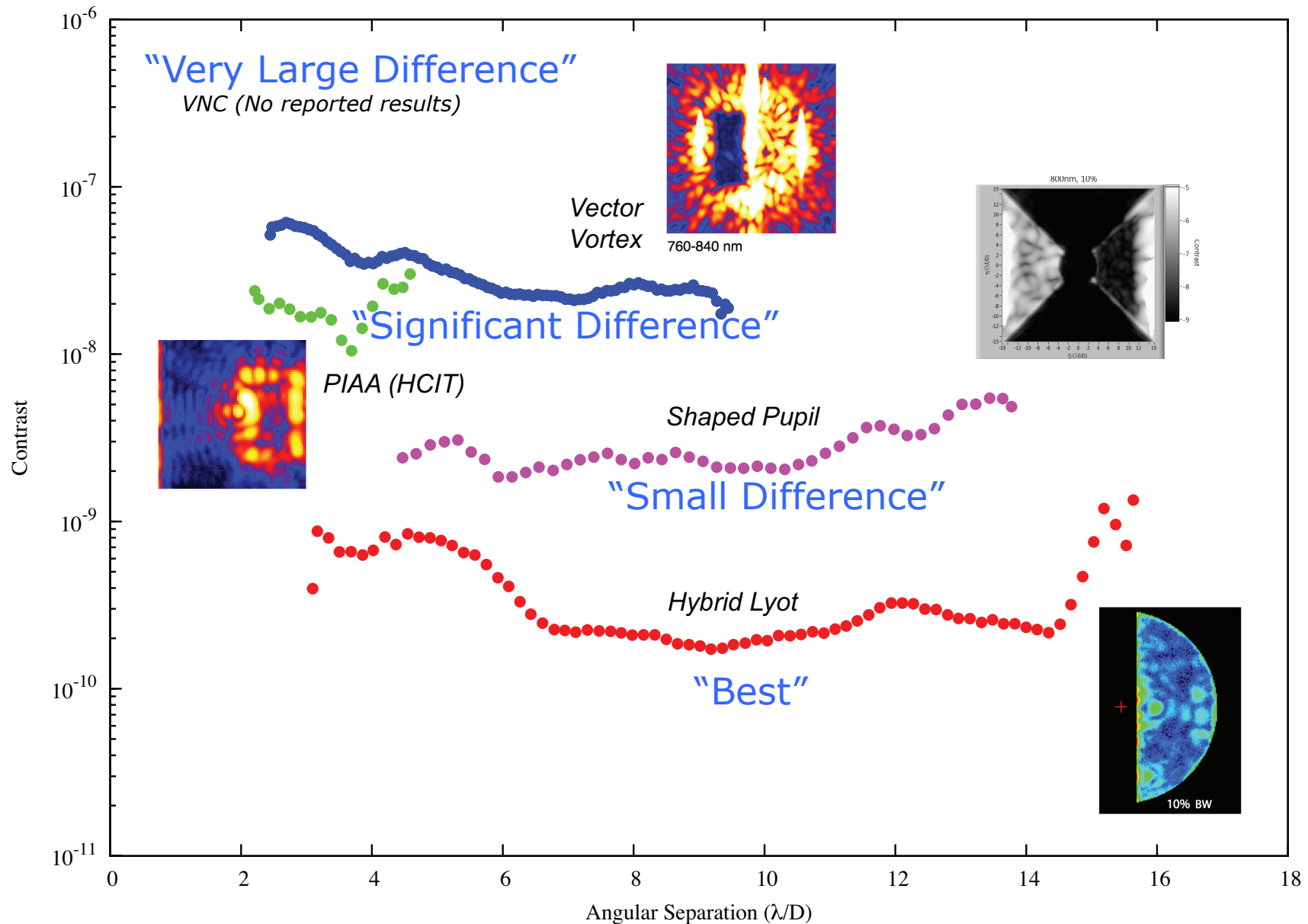
**Acronyms:**

ExEPO: Exoplanet Expl. Prog. Office  
ASO: AFTA Study Office  
SDT: Science Definition Team  
FOM: Figure of Merit  
TRL: Technology Readiness Level

**TAC: Technical Analysis Committee**

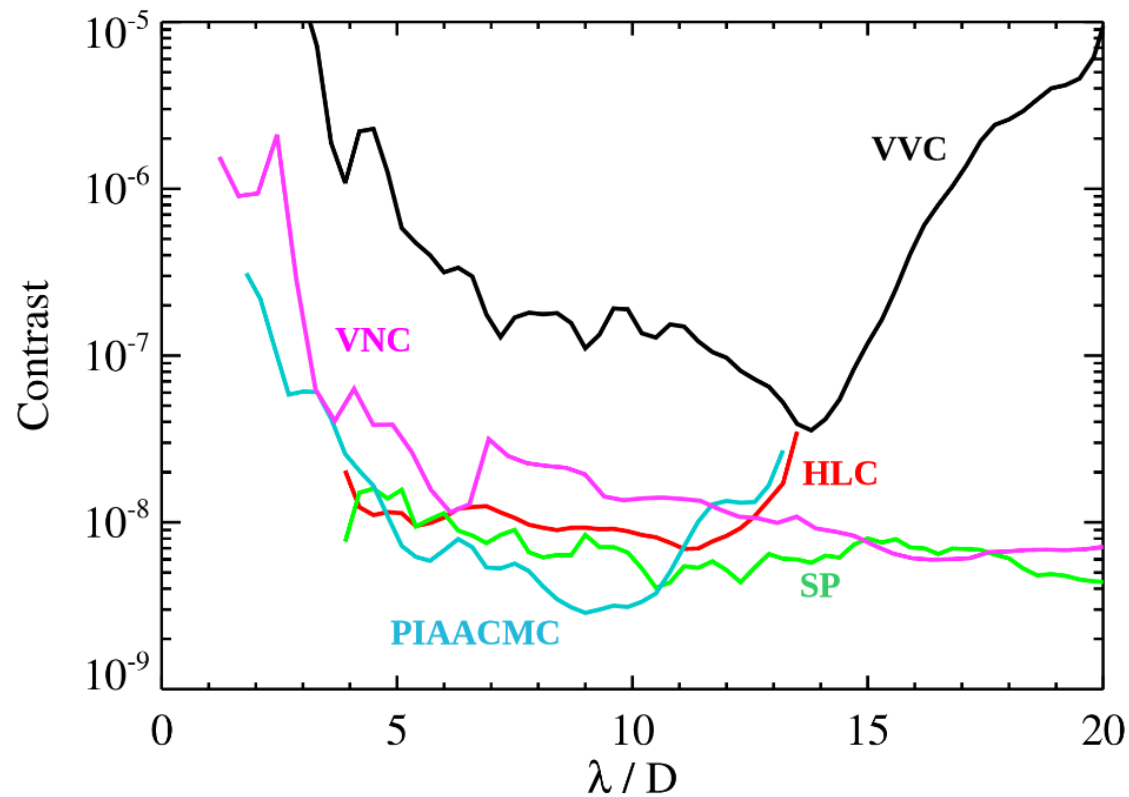
Alan Boss (Carnegie Inst.)  
Joe Pitman (EXSCI)  
Steve Ridgway (NOAO)  
Lisa Poyneer (LLNL)  
Ben Oppenheimer (AMNH)

# 10% Bandwidth Results and Relative Assessment using an un-obscured pupil



## Intermediate Result: Contrast vs Angle from Star

### Modeling Results Summary 1.6 mas RMS jitter



Each coronagraph's performance scales differently depending on jitter.



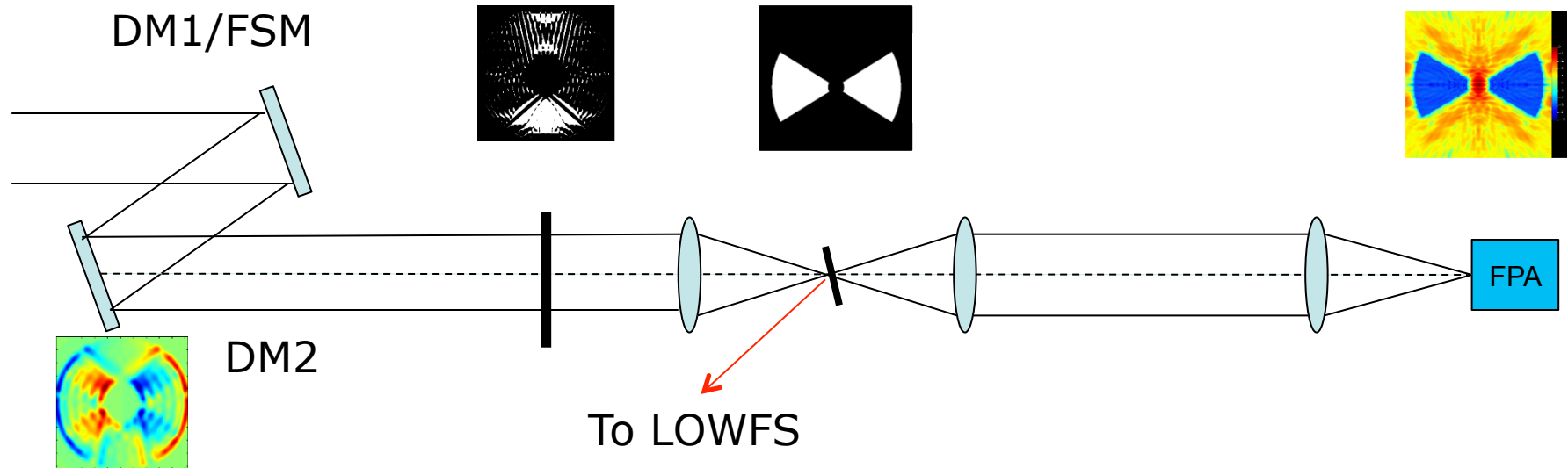
# Executive Summary



ExoPlanet Exploration Program

- **Intended Results of this Briefing:**
  - Provide Recommendation for Primary and Backup coronagraph architectures for AFTA
  - Request APD approval and announcement
- **Executive Summary:**
  - Community working group conducted an open, technical evaluation using public evaluation criteria in a series of workshops and telecons since July 2013
  - We reached a broad consensus on the basis for the recommendation
  - Three strong technologies emerged, spanning the risk/performance continuum
  - The independent Technical Analysis Committee (TAC) concurred with the basis and with findings of ACWG
  - Recommendation:
    - **Primary Architecture:** Occulting Mask Coronagraph (OMC) that includes masks for Shaped Pupil Coronagraph (SPC) and Hybrid Lyot Coronagraph (HLC)
    - **Backup Architecture:** Phase-Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC)
  - Recommendation best minimizes risk, preserves options to protect the project schedule, advances technologies, and preserves possibilities of increased science yield
  - Plan for Recommendation to reach TRL 5 is feasible (technically) and credible within existing resources (schedule, cost)

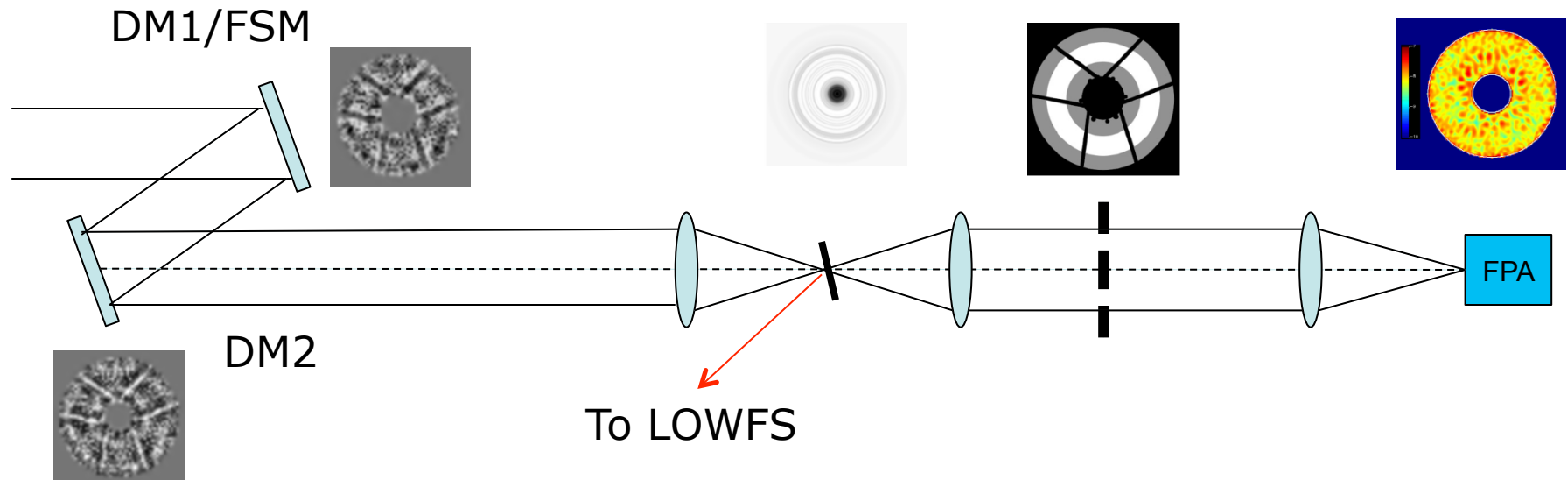
# Shaped Pupil



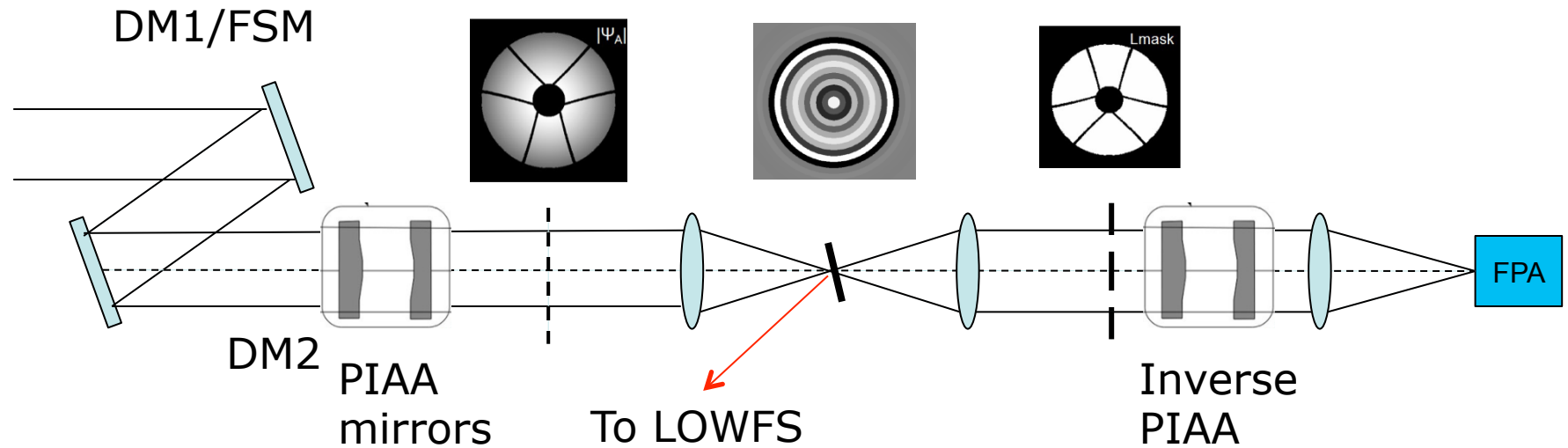
DM1, DM2	Pupil mapping	Apodizer mask	Focal plane mask	Lyot stop	Inverse pupil mapping
Mild ACAD on both DMs		Binary reflection on filter wheels	Binary transmission, on filter wheel		

*ACAD: Adaptive Correction of Aperture Discontinuities*

# Hybrid Lyot



DM1, DM2	Pupil mapping	Apodizer mask	Occulting mask	Lyot stop	Inverse pupil mapping
Mild ACAD on both DMs			Complex transmission, on filter wheel	Transmission, grey, fixed	



DM1, DM2	Pupil mapping	Apodizer mask	Occulting mask	Lyot stop	Inverse pupil mapping
Medium ACAD on both DMs	PIAA mirrors	Gray scale, filter wheels?	Phase transmission, on filter wheel	Transmission, binary, fixed?	Inverse PIAA mirrors



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## Coronagraph Goals: Very Briefly



ExoPlanet Exploration Program

- Directly image RV planets in several visible-wavelength bands
- Obtain R=70 spectra at red wavelengths
- Directly image debris disks, at the level of 100x solar system



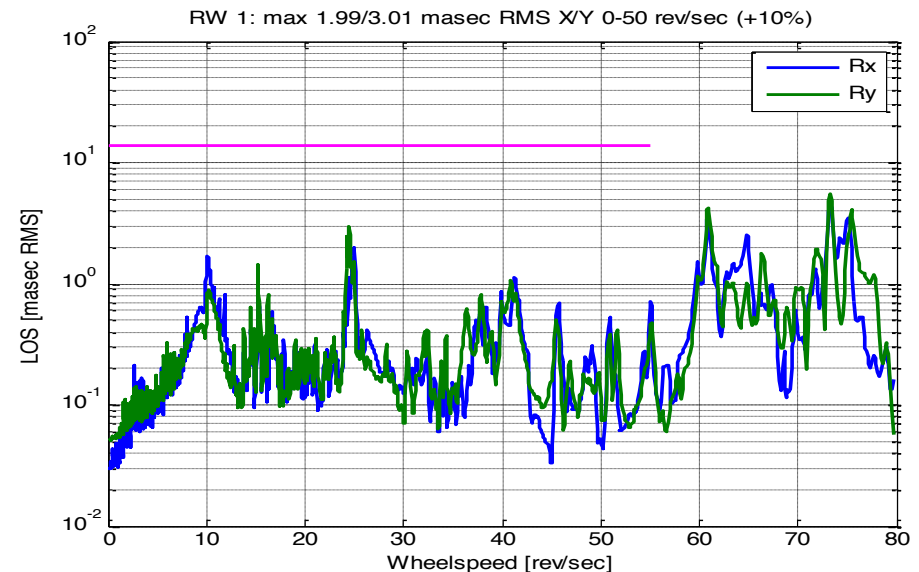
## AFTA Coronagraph Current Status



ExoPlanet Exploration Program

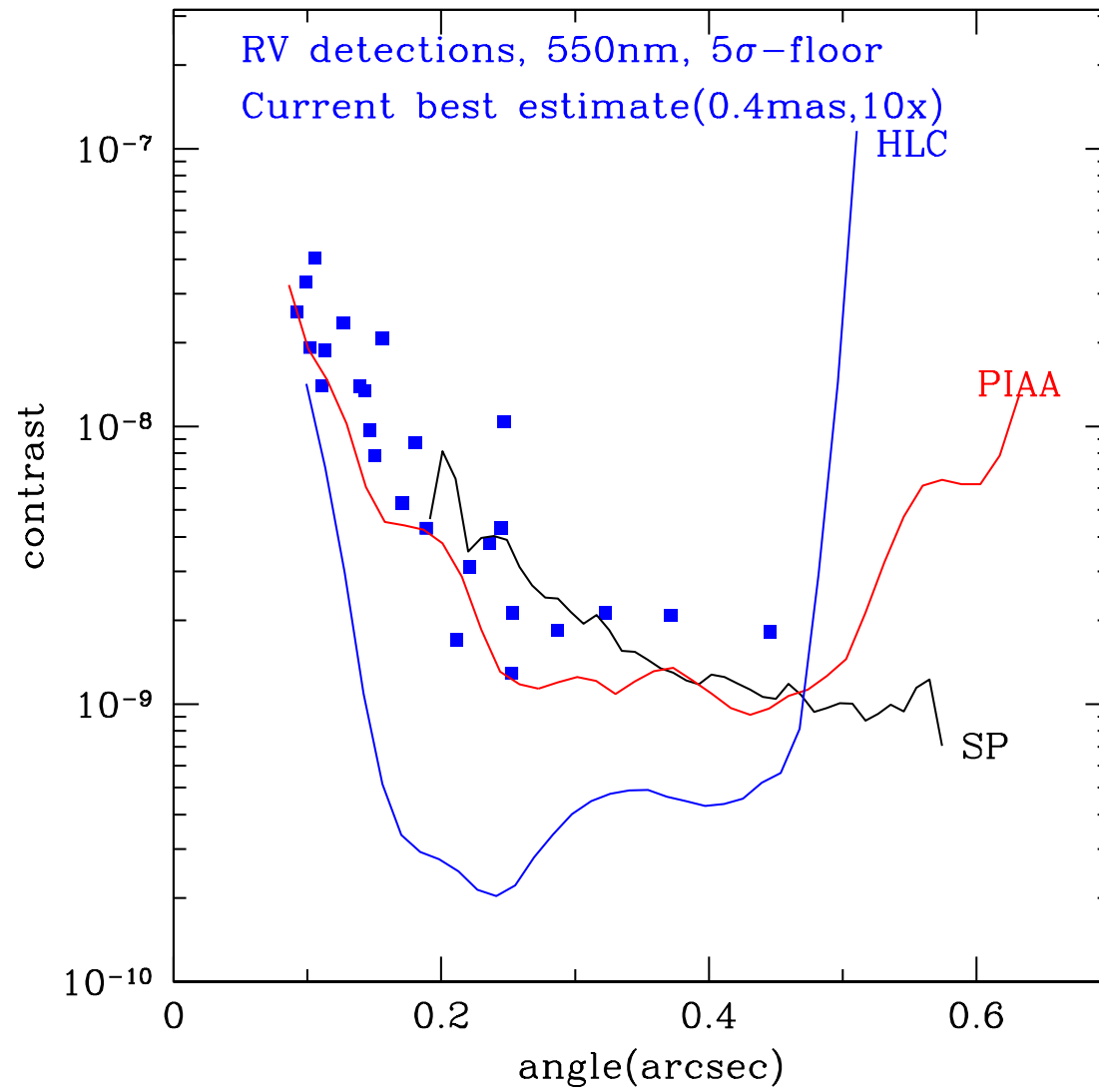
- The AFTA Study Office and SDT continue to study the performance of the observatory and coronagraph for exoplanet direct imaging
- Further modeling has been done of the jitter performance of the observatory. **Current best estimate is 0.4 mas** after the low order wavefront suppression (see slide 3), with a **goal of 0.2 mas**.
- Post-processing improvement in speckle reduction is applied at the **current best estimate of 10x reduction and goal of 30x reduction**
- Updated models have been developed for the HLC coronagraph. The SP and PIAA have new models in development, but not evaluated here.
- Updated estimates of radial velocity exoplanet detections have been made based on the new jitter values, speckle reduction estimates and coronagraph models.

- The Study Office continues to increase the fidelity of the observatory jitter model.
- Results were recently completed that incorporated damping into the finite element model inherent in the existing telescope hardware interface.
- The results indicate telescope **LOS jitter less than 4 mas** over a wide range of wheel speeds. This equates to **0.4 mas after LOWFS**.
- Much work lies ahead as the design of the observatory matures and the structural model fidelity is increased to track that design.
- Numerous opportunities exist for further jitter reduction: operational constraints, momentum management, structural redesign, along with an ETE integrated pointing simulation under development to incorporate further fidelity into the jitter projections.



# Contrast vs Angle from Star

## Current best estimate jitter & post-processing factor



- RV exoplanet detections are estimated based on imaging of radial velocity planets from the current RV catalog

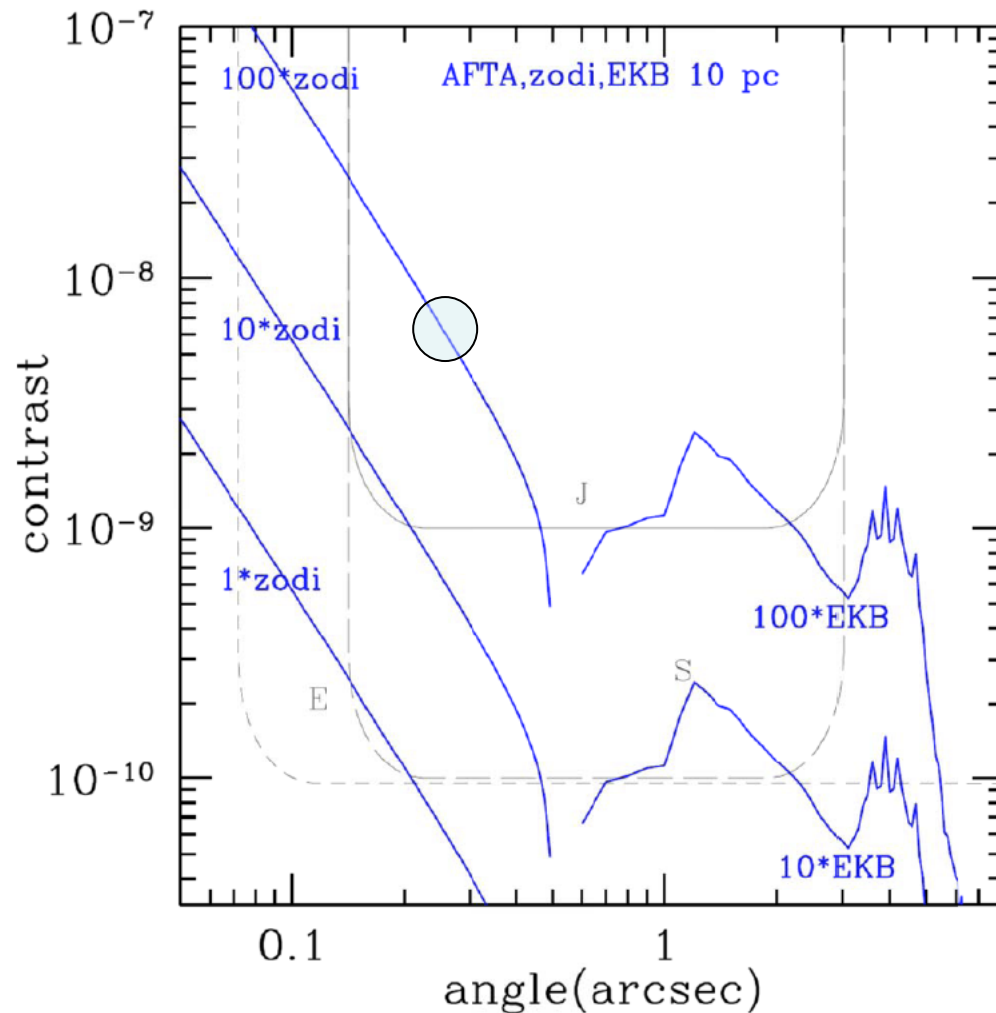
Configuration	Architecture	radial range (arcsec)	median $5\sigma$ detection floor contrast ( $10^{-10}$ )	# RV planets, 550nm band, 6-month campaign	# spectral bands per target, 6-month campaign
<b>Prime</b> (OMC: Occulting Mask Coron.)	<b>SP</b>	0.19 - 0.57	<b>13</b> 4	<b>4</b> 7	<b>4.3</b> 4.9
	<b>HL</b>	0.10 - 0.51	<b>5</b> 1	<b>18</b> 19	<b>4.3</b> 4.2
<b>Backup</b>	<b>PIAA</b>	0.09 - 0.63	<b>19</b> 6	<b>23</b> 30	<b>3.2</b> 4.3

Note 1. Two rows for contrast and # RV images columns are for cases of

- Current Best Estimate: 0.4 mas RMS jitter & 1 mas star, 10x post-processing factor (slide 4)
- Goal: 0.2 mas RMS jitter & 1 mas star, 30x post-processing factor (slide 5)

Note 2. Spectral bands are 10% wide, centered at 450, 550, 650, 800, 950 nm

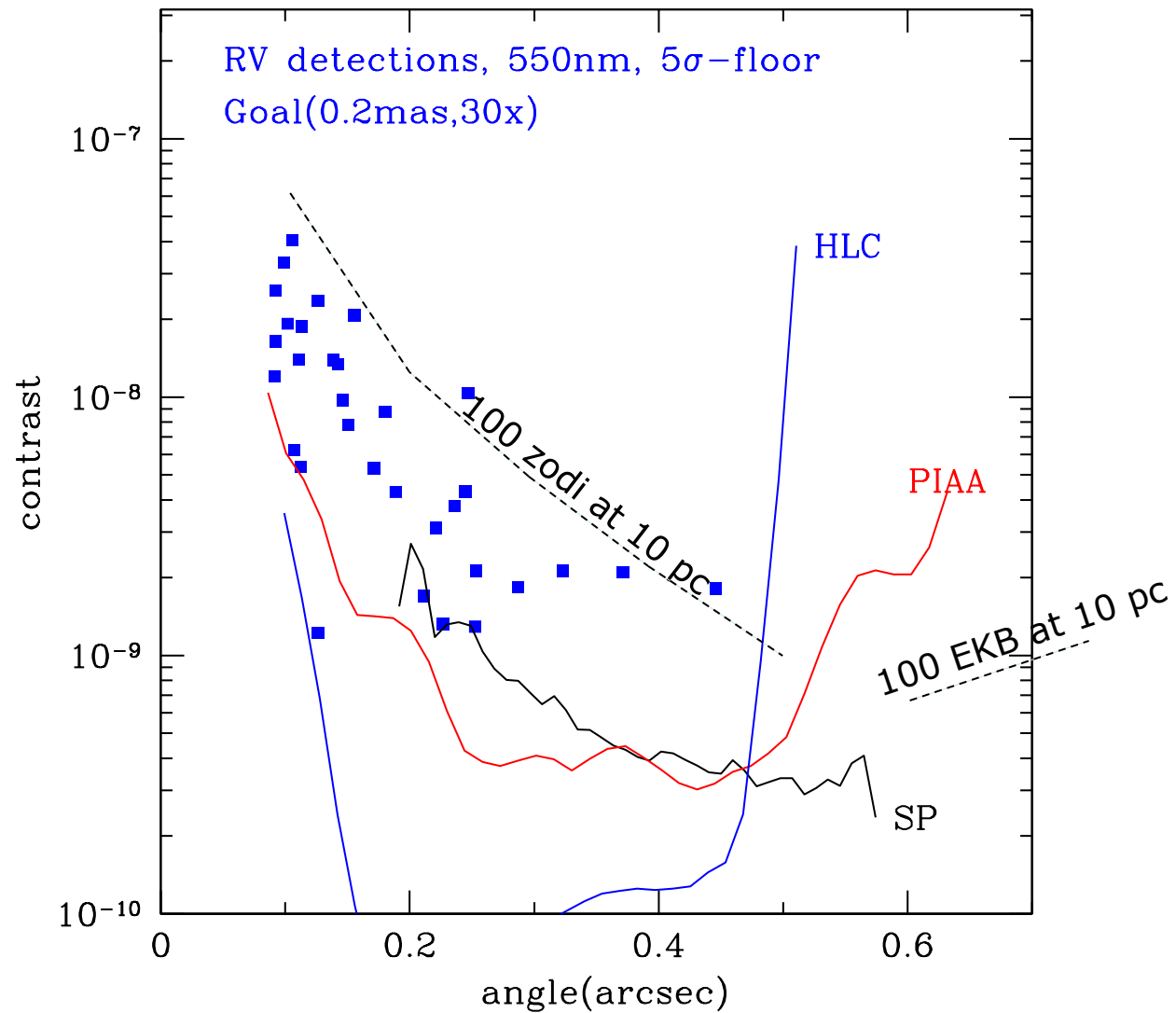
## Zodi-equivalent planet



A 100-zodi disk element at 0.25 arcsec is equivalent to a point-source planet at a contrast of  $6 \times 10^{-9}$ .

# Contrast vs Angle from Star

## Goal jitter & post-processing factor



- RV exoplanet detections are estimated based on imaging of radial velocity planets from the current RV catalog

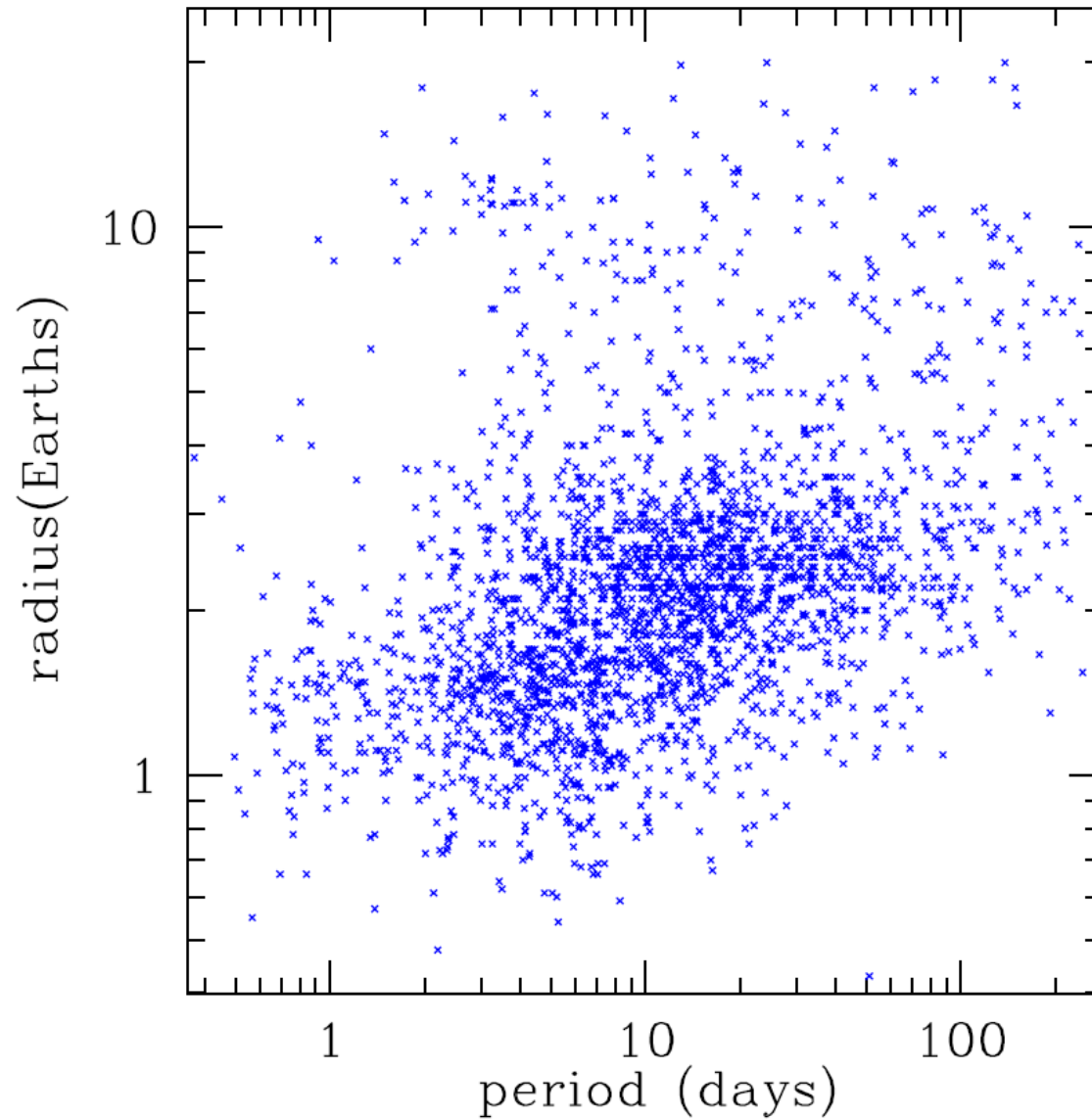
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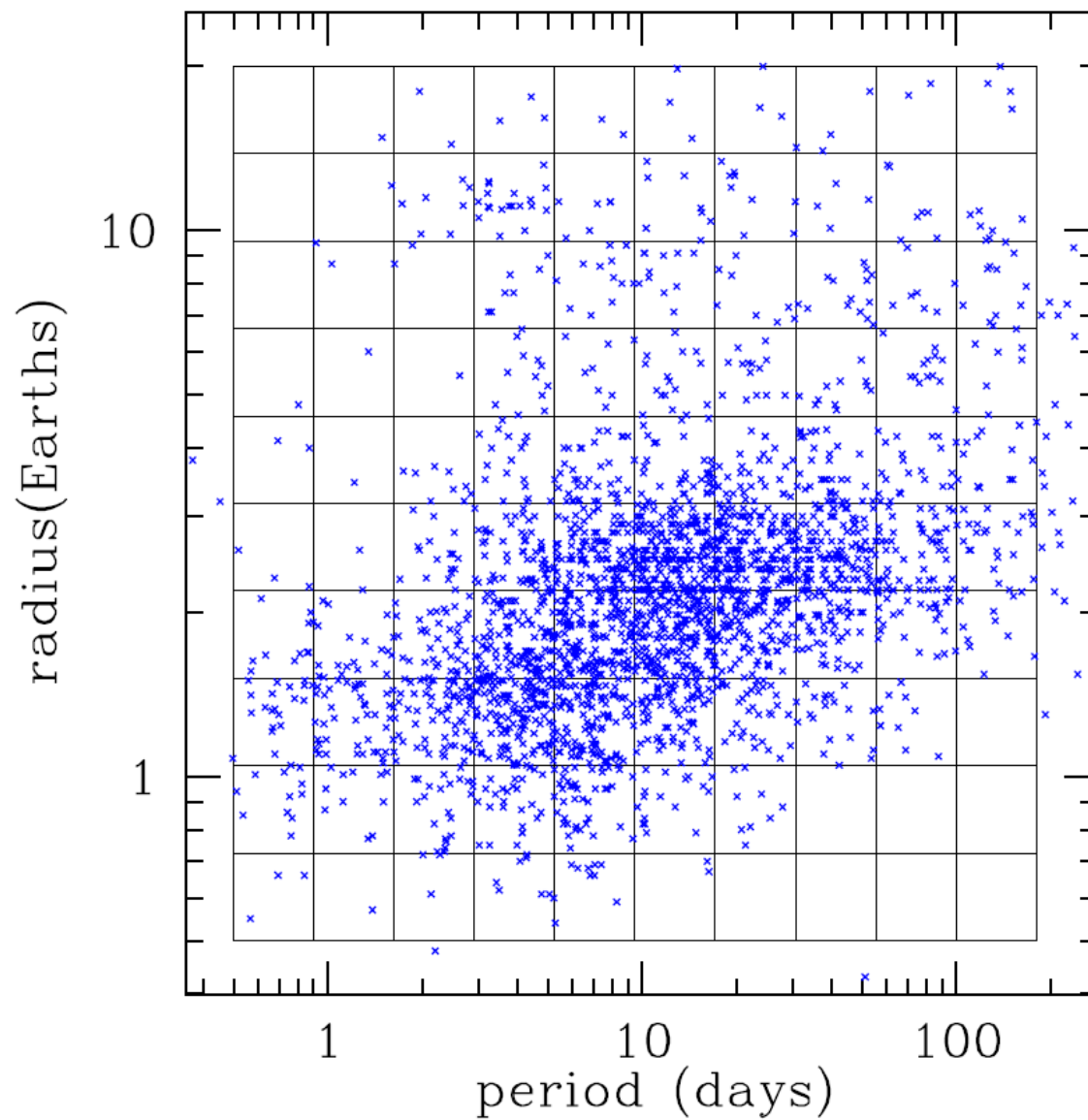
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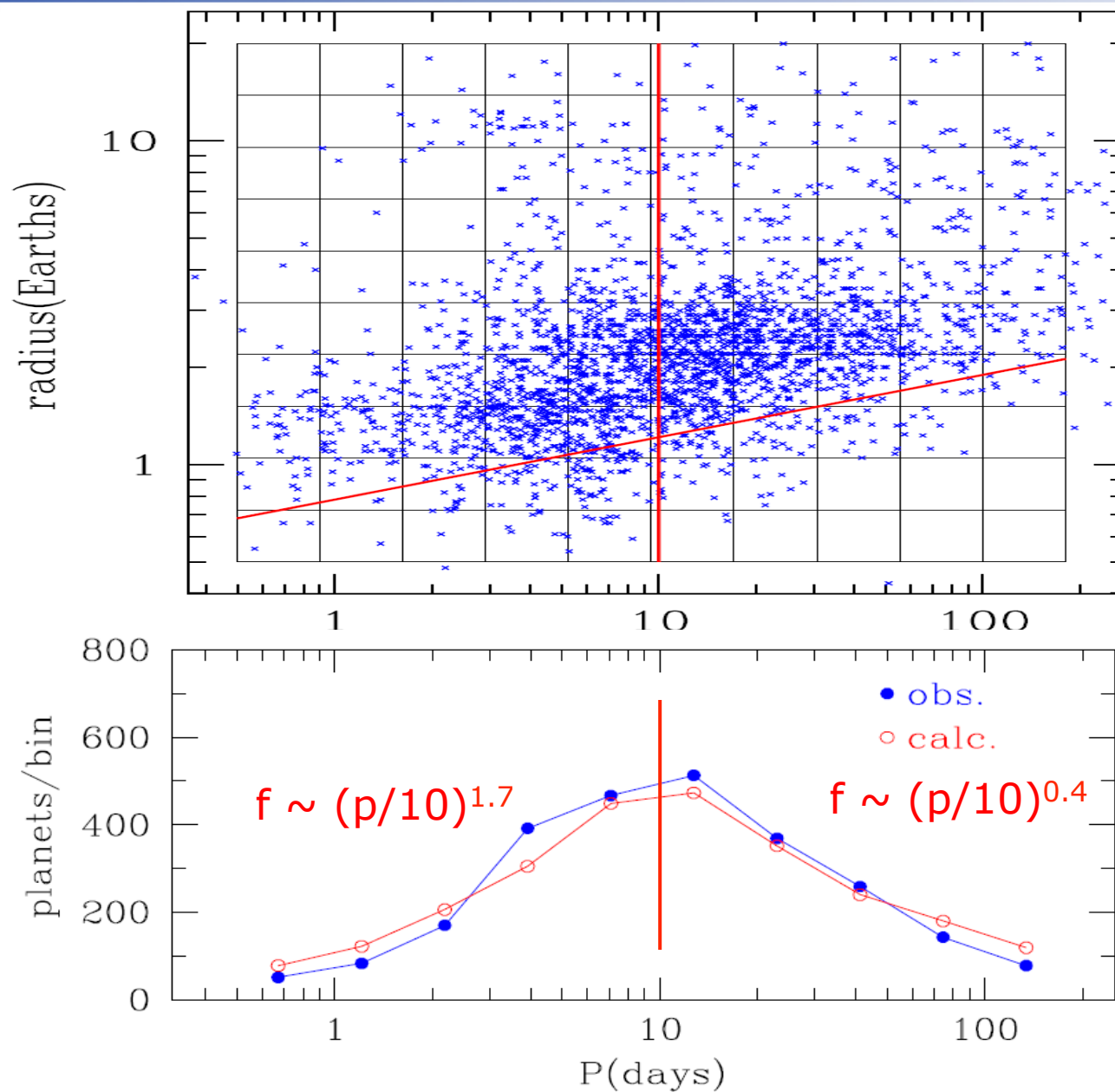
## Kepler (P,r) values (early 2013 data)



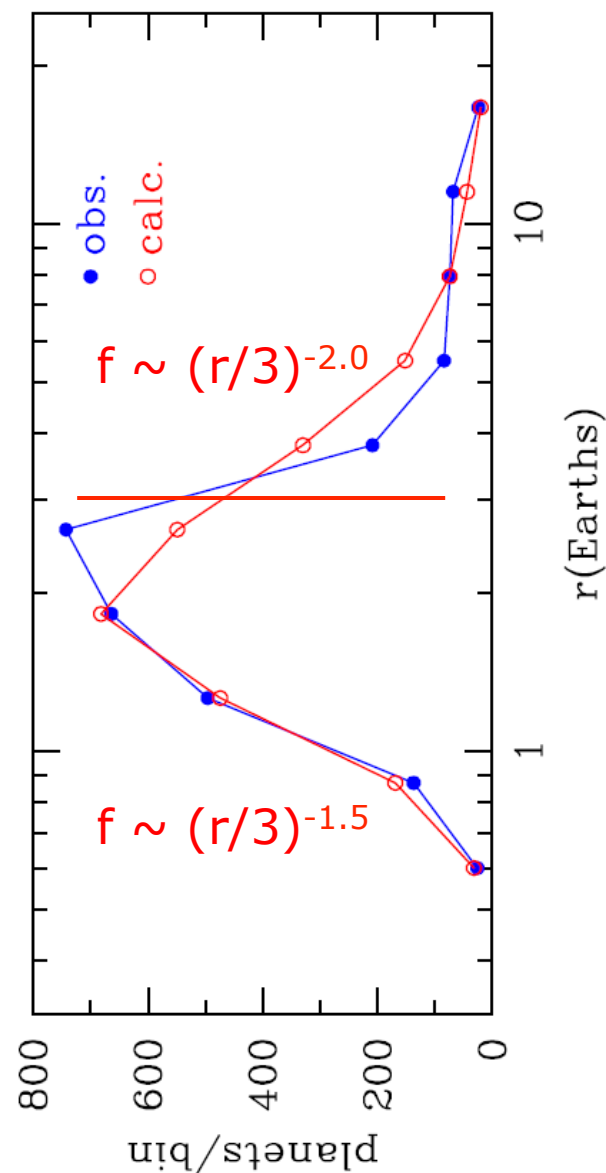
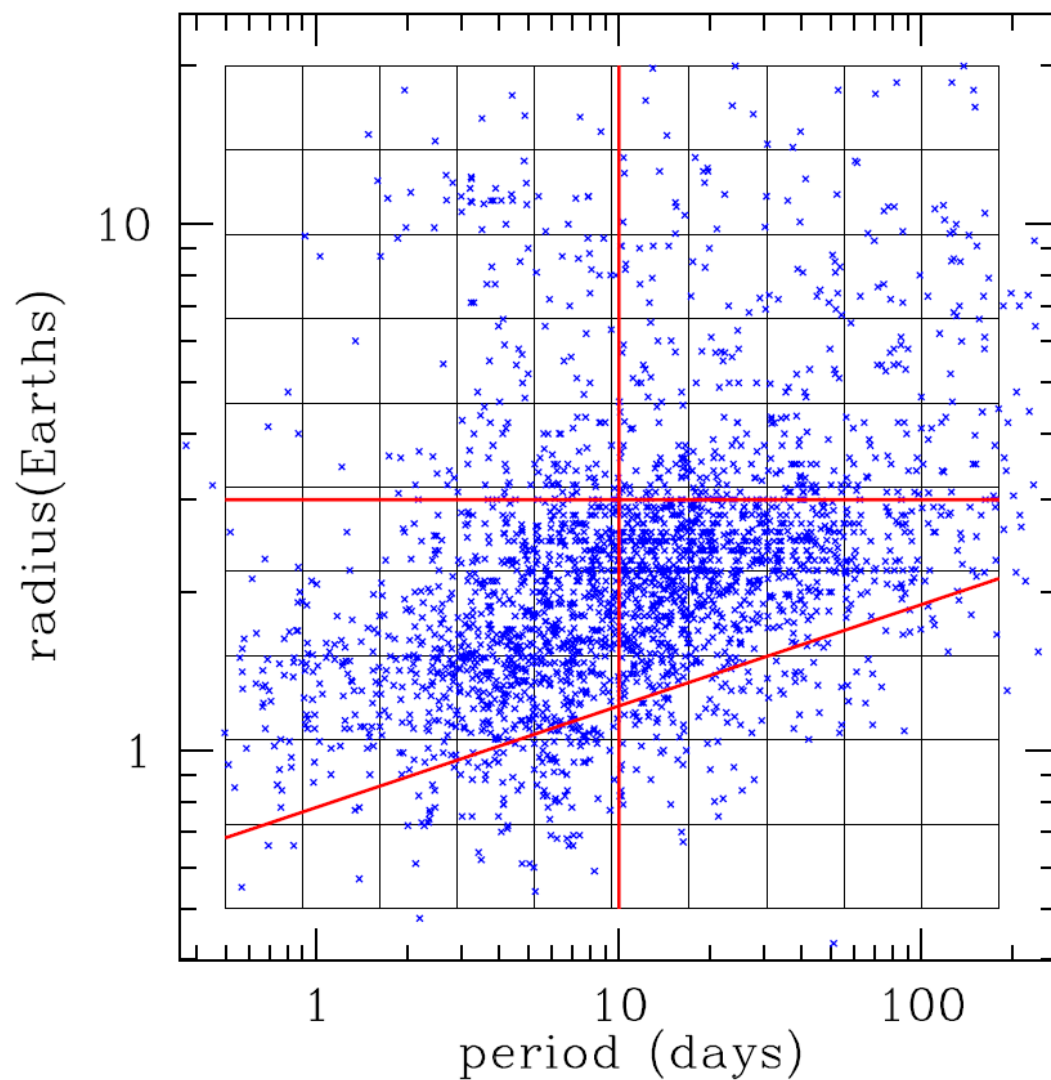
## With superposed grid



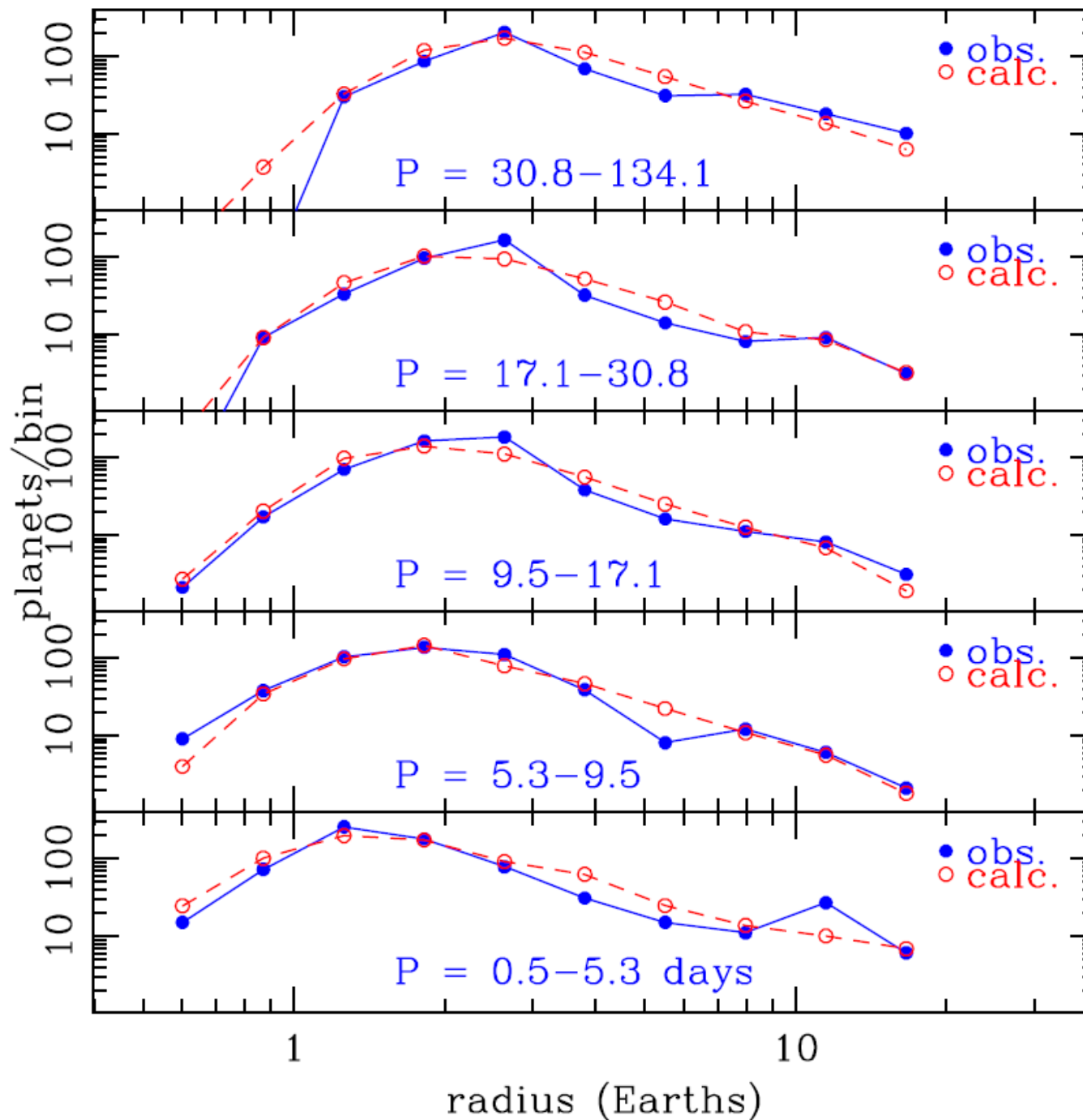
## Period: broken power law in the population



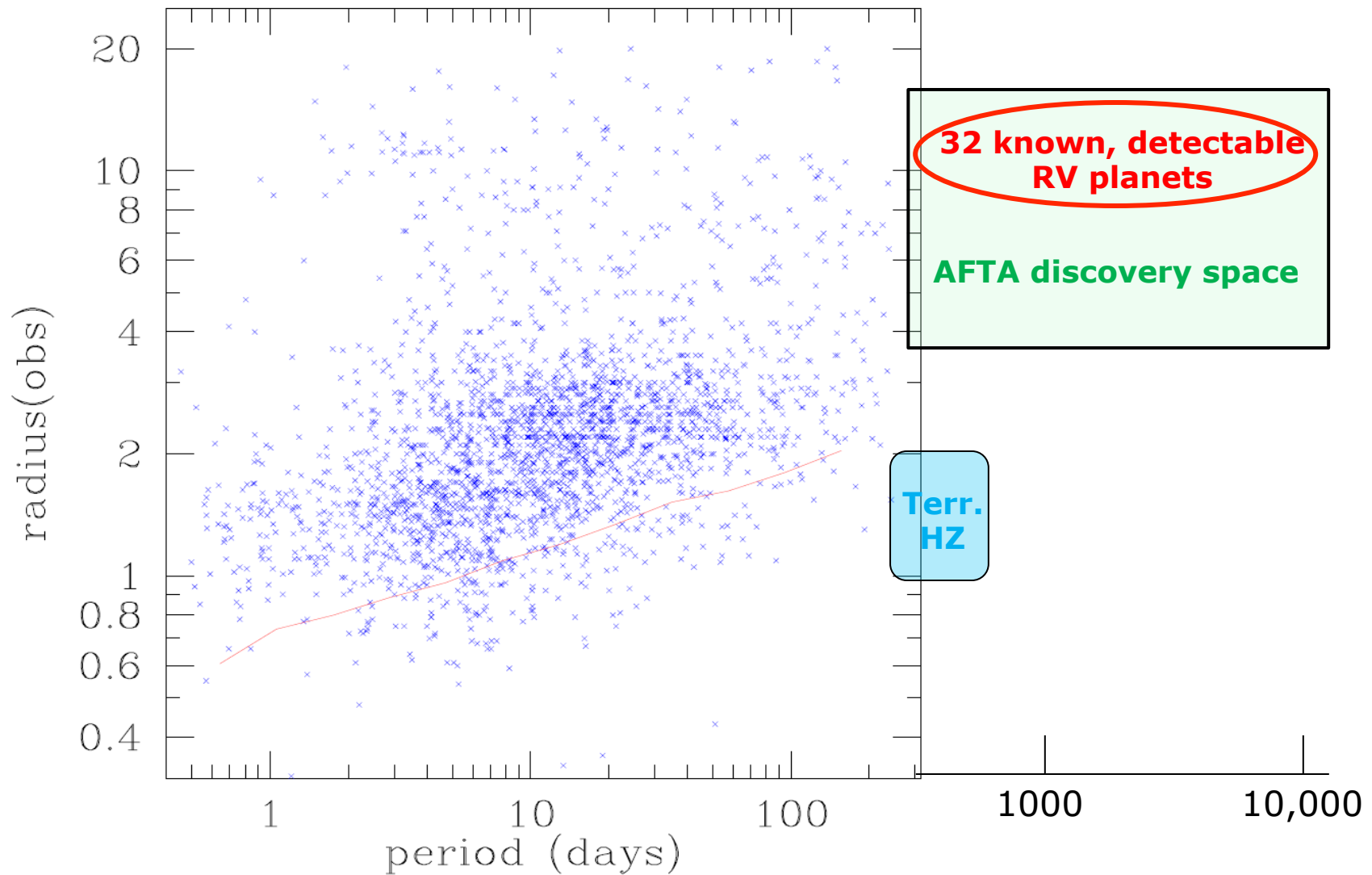
# Radius: broken power law in the population



with broken  
power laws  
&  $r(\text{min})$  cutoff,  
get model fit  
with  
reduced  
chi-square  
 $\sim 1$



# AFTA coronagraph targets





## Summary



ExoPlanet Exploration Program

- The AFTA coronagraph will detect  $\sim 20$  known RV planets (Jupiters)
- Each RV planet will be observed in  $\sim 4$  photometric (10%) bands
- TBD RV planets will have spectra at  $R \sim 70$
- TBD new planets will be found, down to few-Earth radius sizes
- TBD zodi & EKB disks will be found



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